

Thick-film Sensors for Agricultural Applications

M. S. P. LUCAS*; L. E. STEPHENS†; W. H. DAWES‡; M. R. CASEY§

A relative-humidity sensor and two types of soil moisture sensors (capacitance and thermal-conductivity), designed for mass production at low unit costs, were developed by the use of thick-film, hybrid, microelectronic technology and tested in the laboratory. The relative-humidity sensor operates over the range from zero to 100% r.h. and is not damaged by immersion in water. It consists of a platinum-gold electrode structure that is screened and fired on an alumina substrate and then coated with a thin layer of $\text{CaSO}_4 \cdot \frac{1}{2}\text{H}_2\text{O}$ (plaster of Paris). The capacitance soil-moisture sensor operated best in the range from zero to 10% moisture content by weight when tested in Graded Ottawa Sand; the sensor consists of two coplanar, thick-film electrodes with interlocking fingers that are covered with a thin overlayer of glass. The thermal conductivity soil-moisture sensor operated best in the range from zero to 10% moisture content by weight when tested in Graded Ottawa Sand but will work up to saturation at approximately 23%. It consists of a thick-film heater and a sensing thermistor that are screened and fired on opposite sides of an alumina substrate. Both heater and thermistor are covered with a thin layer of overglaze and, if necessary, can be further coated with epoxy resin.

1. Introduction

One of the major obstacles to the widespread use of electronics in agriculture is the lack of reliable and inexpensive sensors to transfer information from the sometimes hostile agricultural environment to the electronics. This paper describes the construction and design details of three inexpensive but rugged sensors that were fabricated by means of thick-film, hybrid, microelectronic technology. One of the sensors was developed primarily to measure the relative humidity in the atmosphere within a mass of stored grain; the other two sensors (capacitance and thermal-conductivity) were developed to measure the moisture content of soils. Two of the sensors can also be used for other applications, including temperature sensing and level sensing of certain liquids.

2. The thick-film process

In the thick-film process, layers of conductive, resistive, or dielectric inks are screen printed upon a ceramic substrate. The inks are dried and then fired in a continuous belt furnace at temperatures ranging from 250 to 1000° C depending upon the type of ink used.

The inks consist of finely powdered precious metals, glass frits, and liquid vehicles that are ground together to form a thick viscous paste; the conductive, resistive, or dielectric properties of the inks are not evident until after the firing process.

The printing screens are formed by tightly stretching fine mesh nylon, polyester, or stainless steel cloths over a rigid frame. A thick-film pattern is printed on the screen by coating it with a photographic emulsion, and then exposing and developing the emulsion in order to leave "windows" in those areas where a circuit element is to be formed on the ceramic substrate. The ink is forced through the windows by a plastic squeegee.

The thick-film process^{1, 2} is widely used in the electronics industry and is frequently a highly automated process; nevertheless, it can also be used as an inexpensive laboratory process to produce small quantities of special components. Such a system has been described by Lucas and Dawes.³

*Associate Professor, Electrical Engineering Department, Kansas State University, Manhattan, Kansas 66506, U.S.A.

†Agricultural Engineer, Agricultural Research Service, U.S. Department of Agriculture, Manhattan, Kansas 66502, U.S.A.

‡Secretary, ICE Corporation, Manhattan, Kansas 66502, U.S.A.

§Production Manager, ICE Corporation, Manhattan, Kansas 66502, U.S.A.

Received 2 December 1974; accepted in revised form 14 February 1975



Fig. 1. Relative-humidity sensor formed from platinum-gold electrodes with interlocking fingers covered with a layer of $\text{CaSO}_4 \cdot \frac{1}{2}\text{H}_2\text{O}$ (plaster of Paris)

3. Relative-humidity sensor

The thick-film relative-humidity (r.h.) sensor is an improvement of a type of sensor developed by Bouyoucos⁴ for measuring soil moisture under field conditions. The Bouyoucos sensor consists of a block of $\text{CaSO}_4 \cdot \frac{1}{2}\text{H}_2\text{O}$ (plaster of Paris) within which are imbedded two stainless steel electrodes 0.94 in long by 0.50 in wide and separated by 0.25 in of plaster of Paris. Each block is 1.50 in long by 1.00 in wide by 0.50 in thick. When the block is buried in soil it absorbs

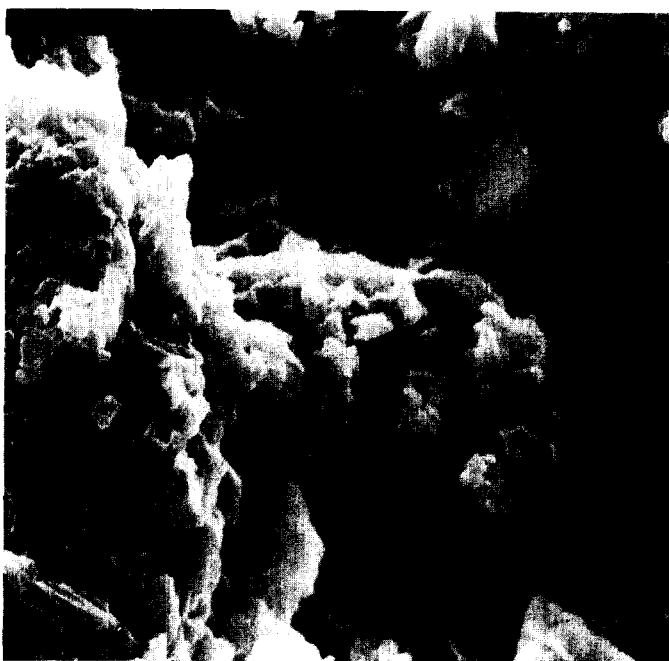


Fig. 2. Scanning electron micrograph of sensor surface, showing open pores and large internal surface area of the plaster of Paris ($\times 4,000$)

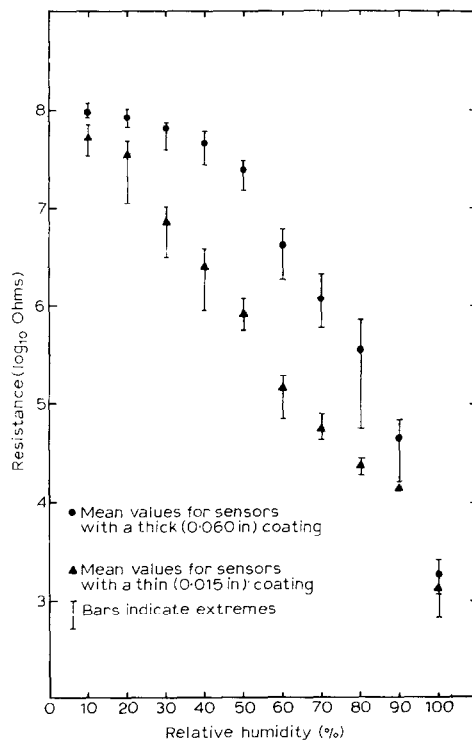


Fig. 3. Resistance as a function of relative humidity for plaster of Paris-coated relative-humidity sensors

moisture, which produces a change in the electrical resistance between the electrodes. This resistance can be calibrated in terms of the soil's moisture content.

Bouyoucos⁵ has also reported that the blocks can be used to measure relative humidity over the range from 12 to 100% r.h. with an accuracy of between 1 and 2% up to 75% r.h., and between 2 and 3% from 75 to 100% r.h. The measurements are independent of temperature between 2 and 32° C.

The thick-film r.h. sensor was designed to overcome some of the deficiencies of the Bouyoucos sensor, particularly its limited range and slow response. An important requirement was that

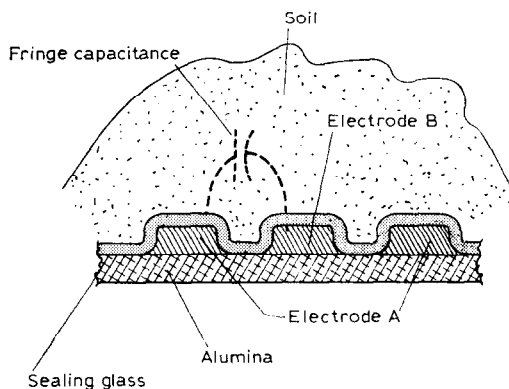


Fig. 4. Diagram showing the principle of operation of a capacitance soil-moisture sensor. This sensor detects the variation in fringe capacitance in a coplanar electrode structure with interlocking fingers

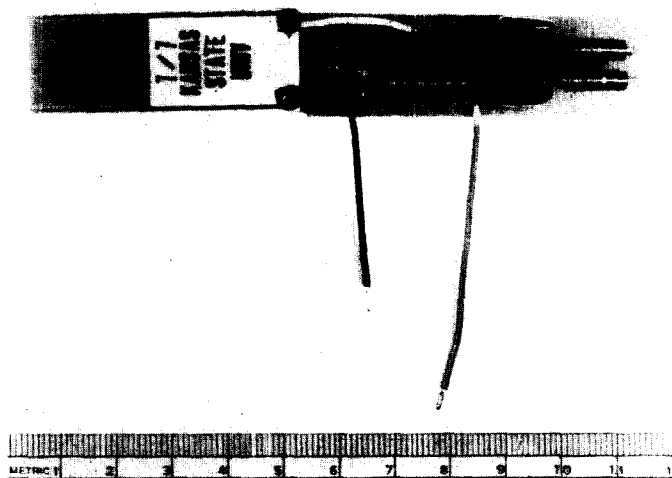


Fig. 5. Photograph of capacitance soil-moisture sensor attached to a micropower, radio-telemetry transmitter

the improved sensor could be produced economically in quantity and have only small differences between the characteristics of individual sensors. Two photographs of the thick-film r.h. sensors are shown in Fig. 1. The photograph on the left shows the coplanar, interlocking electrode fingers; the other photograph shows the completed sensor after it was coated with plaster of Paris. The electrode material is Plessey C 6110 Platinum Gold, which is screened and fired on a 96% alumina substrate. The electrode's line widths and spacings are 0.007 in and the best sensor characteristics were obtained with a layer of plaster of Paris approximately 0.037 in thick. The scanning electron micrograph of the sensor surface in Fig. 2 shows the open pores and large

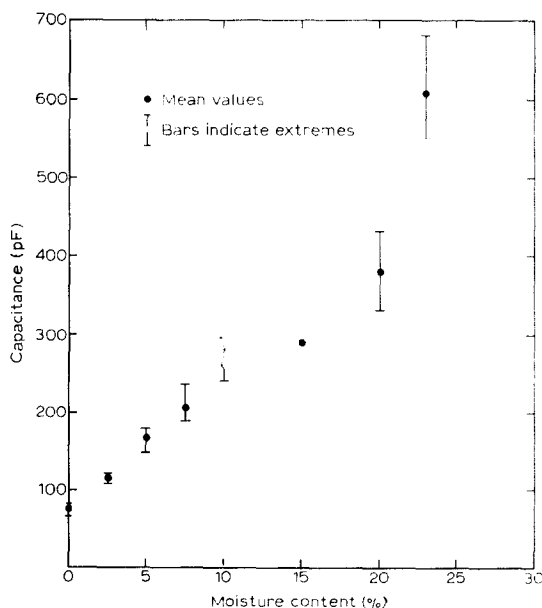


Fig. 6. Capacitance as a function of percent water content by weight in Graded Ottawa Sand (ASTM C-109)

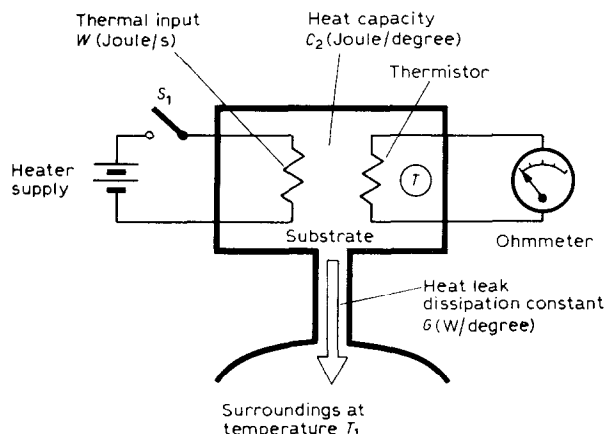


Fig. 7. Diagram showing the principle of operation of the thermal-conductivity soil-moisture sensor

internal surface area of the plaster of Paris, which contribute to the sensor's sensitivity and rapid response. The reduced thickness of the plaster of Paris layer and the close spacing of the electrodes also improve the performance over that of the Bouyoucos sensor.

In Fig. 3 two sets of measurements are shown; one for sensors with 0.015 in coating of plaster of Paris and one for sensors with a 0.060 in coating. Presumably the variation of resistance as an inverse logarithmic function of relative humidity is a result of proton transfer in the electric field between the electrodes. The same electrode structure was used for both sets of measurements. Alternating current of 60 Hz was used in making the measurements. Direct-current measurements are not useful, because the sensors polarize. The voltages applied were equal to or less than 10 volts r.m.s. but no dependence of resistance on voltage was observed. The controlled-humidity atmospheres were obtained from calibrated glycerine and water solutions.⁶

An important characteristic of this sensor is that it can be cleaned periodically with water or occasionally subjected to immersion or water condensation and dried without need for recalibration.

The feasibility of using the sensors to monitor the moisture content of stored grain is being evaluated at the U.S. Grain Marketing Research Center, Manhattan, Kansas. A system is

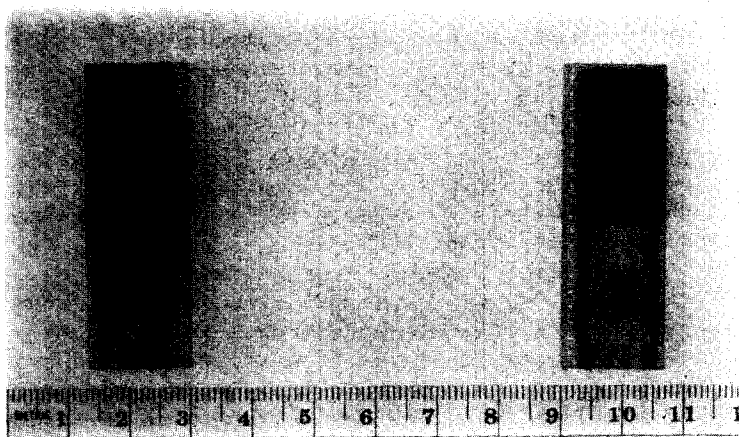


Fig. 8. Photograph of both sides of a thermal-conductivity soil-moisture sensor, showing thermistor and heater resistance

envisaged that will provide moisture-content information from numerous locations within a storage structure in the same manner in which thermocouples now provide temperature monitoring. The concept relies on knowing the equilibrium relative humidity of the stored grain, information which is readily available for most grains. No short-term drift in the sensor's calibration has been observed, but long-term drift, particularly the effect of accumulated grain dust, is still under investigation.

4. Capacitance soil-moisture sensor

The operation of a capacitance soil-moisture sensor depends upon the fact that the dielectric constant of water is about 80; whereas, that of a normal, completely dry soil is about 2.6. Consequently, the presence of a relatively small amount of water in the soil causes a large change in the effective dielectric constant. This change of dielectric constant results in a change of capacitance that can be calibrated in terms of the water content of the soil in percent by weight.

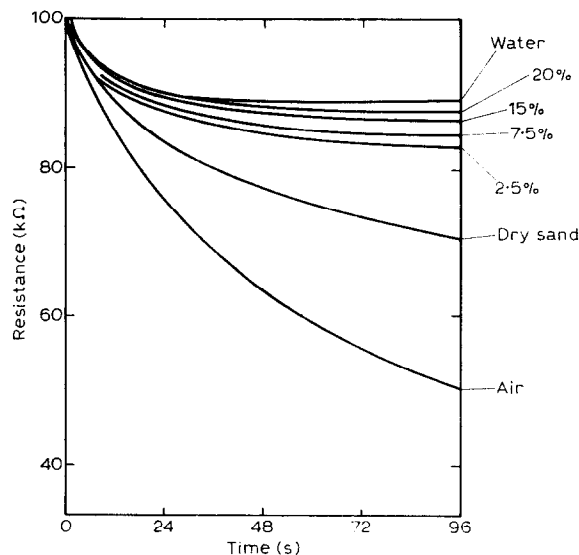


Fig. 9. Resistance as a function of time at a constant power input for various values of moisture content for an epoxy encapsulated thermal-conductivity soil-moisture sensor; heater energized at time $t = 0$; power input, 1 watt

The principle of operation of the capacitance soil-moisture sensor can be explained by reference to Fig. 4, which shows a cross-section of a microcomb-capacitor sensor. Note that the fringe capacitance between the fingers of electrodes A and B is a function of the dielectric constant of the material in the vicinity of the electrodes. The contribution of the capacitance on the substrate side is practically constant because of the relative thickness of the substrate. The contribution of the capacitance on the other side is a variable that depends upon the moisture content of the material adjacent to the glass overglaze. For optimum results the glass overglaze must be as thin as possible and completely free of pinholes.

A photograph of a thick-film, microcomb-capacitor soil-moisture sensor is shown in Fig. 5. This particular sensor is attached to an experimental micropower radio-telemetry transmitter. The active area of the capacitor is 0.88 in by 0.75 in, and the electrode structure is identical to that used for the relative-humidity sensor described in the previous section. It consists of two coplanar, platinum-gold electrodes, with interlocking fingers which have a line width and spacing of 0.007 in, that are screened and fired on one side of a 96% alumina substrate. The electrodes are isolated from the soil by a thin layer of No. 4770-B-Clear Glass overglaze, manufactured by Electro-Science Laboratories.

A typical capacitance soil-moisture sensor has a capacitance of 55 picofarads (pF) in dry air, 75 pF in dry soil, and 750 pF in clear water. The data in *Fig. 6*, which shows capacitance in pF as a function of percentage of water content by weight in Graded Ottawa Sand (ASTM C-109), were obtained with a Boonton 72AD capacitance meter at an operating frequency of 1 MHz. Note that the capacitance sensors are reasonably precise in the range from zero to 10% moisture content by weight; they are less precise in the range from 10% to saturation, which is approximately 23%. The poor precision in the upper range results from the difficulty in compacting the sand in a repeatable manner around the sensor. The capacitance sensor will also give erroneously high readings in the presence of salt.

The microcomb-capacitor sensor can also be used to detect liquid levels when the dielectric constant of the liquid is different from that of air.

5. Thermal-conductivity soil-moisture sensor

The concept underlying this type of sensor is not new, and much of the pertinent literature has been surveyed by Ballard⁷ and Monfore⁸; however, through use of thick-film technology it appears possible to produce good thermal-conductivity sensors in quantity at acceptable prices.

The principle of this sensor's operation is based on the fact that the thermal conductivity of a soil depends upon its moisture content. Thermal conductivity can be measured by monitoring the power input, temperature rise, and duration of power input to a heat source that is surrounded by the material under study. Since the moisture content of the soil affects its thermal conductivity, such a sensor can be calibrated to read moisture content. A simple model of the thermal sensor is shown in *Fig. 7*. Approximate equations that describe the sensor's behaviour are as follows:

$$\text{heating equation; } T - T_1 = \frac{W}{G} (1 - e^{-Gt/C}) \quad \dots (1)$$

$$\text{cooling equation; } T - T_1 = \frac{W}{G} e^{-Gt/C} \quad \dots (2)$$

$$\text{steady state; } T - T_1 = \frac{W}{G} \quad \dots (3)$$

where

T = temperature of substrate in °C

T_1 = temperature of surroundings

t = time, s

W = thermal input, in Js⁻¹

C = heat capacity of entire sensor in J/°C

G = heat leak or dissipation constant in W/°C

These equations are similar to those that describe the electrical behavior of a simple resistance-capacitance network.

Both sides of a thermal-conductivity sensor are shown in *Fig. 8*. The sensor was fabricated on a 2.00 in by 0.69 in 96% alumina substrate. The heater resistance had a design value of 100 ohms and was printed with DuPont Birox resistor paste. The thermistor was printed with a Plessey EMD cobalt oxide ink, which fires at 1300°C. All conductors were Plessey EMD C-6110 platinum-gold, and both sides of the substrate were isolated with a layer of No. 4770-B-Clear Glass overglaze, manufactured by Electro-Science Laboratories. Some of the sensors were further encapsulated in Stycast 2850 FT thermally conducting epoxy resin.

In *Fig. 9* some recorder plots are shown for thermistor resistance as a function of time for a thermal-conductivity soil-moisture sensor. For these measurements a constant power input of

1 watt was used, and the curves were obtained by immersing the sensor in samples of Graded Ottawa Sand at the indicated moisture contents.

The thermal-conductivity sensor can also be used to detect liquid levels and, by the use of a suitably calibrated thermistor, to measure temperature.

6. Conclusions

Thick-film, hybrid, microelectronic technology can produce relative-humidity sensors and soil-moisture sensors which have lower cost, greater sensitivity, wider operating range, and are less easily damaged than presently available devices. The sensors each measure one of three variable parameters, resistance, capacitance, or thermal conductivity, allowing some flexibility in application choice. The two soil-moisture sensors can also be used for liquid level detection.

Acknowledgements

This work was supported in part by the Kansas State Highway Commission under contract No. 22-5001-9-5450 in a study conducted in cooperation with the U.S. Department of Transportation, Federal Highway Administration; and in part by the U.S. Grain Marketing Research Center, U.S. Department of Agriculture, under cooperative agreement No. 12-14-3001-232.

REFERENCES

- ¹ **Hamer, D. W.; Biggers, J. V.** *Thick-film Hybrid Microcircuit Technology*. New York: Wiley-Interscience, 1972
- ² **Topfer, M. L.** *Thick-film Microelectronics*. New York: Van Nostrand, 1971
- ³ **Lucas, M. S. P.; Dawes, W. H.** *A thick-film microcircuit laboratory*. IEEE Trans. on Educ., 1973 **E16** (3) 130
- ⁴ **Bouyoucos, G. J.** *Plaster-of-Paris block electrical measuring unit for making continuous measurement of soil moisture under field conditions*. In *Humidity and Moisture*, Vol. 4 (Ed. Wexler). New York: Reinhold, 1965
- ⁵ **Bouyoucos, G. J.; Cook, R. L.** *Humidity sensor permanent electric hygrometer for continuous measurement of the relative humidity of the air*. RILEM/CIB Symp. on Moisture Problems in Building, Helsinki, 1965 Vol. II Sec. 6
- ⁶ **Grover, D. W.; Nicol, J. M.** *The vapor pressure of glycerine solutions at 20° C.* J. Soc. Chem Ind., 1940 **54** 175
- ⁷ **Ballard, L. F.** *Instrumentation for measurement of moisture*. NCHRP Report 138, Highway Research Board, National Academy of Sciences, Washington, 1973
- ⁸ **Monfore, G. E.** *A review of methods for measuring water content of highway components in place*. Highway Research Record No. 342, Highway Research Board, National Academy of Sciences, Washington, 1970